Odin's Helmet: A Head-Worn Haptic Feedback Device to Simulate G-Forces on the Human Body in Virtual Reality

MATTHIAS HOPPE, LMU Munich, Germany
DARIA OSKINA, LMU Munich, Germany
ALBRECHT SCHMIDT, LMU Munich, Germany
THOMAS KOSCH, TU Darmstadt, Germany

Virtual Reality (VR) experiences have massively improved in the mediation of feedback. However, the simulation of forces is still limited. This paper presents Odin's Helmet, a head-worn device to simulate g-forces that act on the human head in real-life situations. Odin's Helmet uses four head-mounted propellers as actuators to simulate g-forces through pushing and pulling the user's head while being immersed in VR. Odin's Helmet's goal is to increase presence and manipulate the user's perception of the otolith organ in the vestibular system. The user's perception will be tricked to experience a sensation of self-movement in VR. A technical evaluation shows Odin's Helmet's applicability to apply perceivable g-forces to the user's head. We conclude with future use cases of Odin's Helmet, such as redirected walking by controlling the user's head orientation, attention guidance, and wind simulations through Odin's Helmet.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**; *Haptic devices.*

Additional Key Words and Phrases: Virtual Reality; Haptic Feedback; Head-Worn; Sense of Balance; G-Force

ACM Reference Format:
Matthias Hoppe, Daria Oskina, Albrecht Schmidt, and Thomas Kosch. 2021. Odin's Helmet: A Head-Worn Haptic Feedback Device to Simulate G-Forces on the Human Body in Virtual Reality. *Proc. ACM Hum.-Comput. Interact.* 5, EICS, Article 212 (June 2021), 15 pages. https://doi.org/10.1145/3461734

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1 INTRODUCTION

Recent developments in hardware and computational efficiency made Virtual Reality (VR) accessible to a broad audience. The demand for more immersive experiences and a higher level of presence is rising, especially for audiovisual and haptic feedback. A variety of work has been presented to simulate the virtual environments as thoroughly as possible using auditory [17], haptic [18, 25, 28, 40], or tactile [44] feedback. The simulation of forces in VR, such as gravitational force equivalents (g-forces) and the generation of motion, has been the subject of previous research to a minimal extent. The perception of g-force is an essential factor to consider when simulating forces in virtual environments, contributing to the perceived presence. Controllers and Head-Mounted Displays (HMDs) currently cannot render g-forces. The absence of these forces impacts the visual representation, expected, and perceived feedback negatively, leading to a lowered perception of presence [35]. The concept of mediating forces is not entirely new and several VR projects focused on technologies that enable the perception of forces in VR. Lopes et al. [27] applied electronic

Authors' addresses: Matthias Hoppe, matthias.hoppe@ifi.lmu.de, LMU Munich, Germany; Daria Oskina, daria.oskina@ifi.lmu.de, LMU Munich, Germany; Albrecht Schmidt, albrecht.schmidt@ifi.lmu.de, LMU Munich, Germany; Thomas Kosch, kosch@tk.tu-darmstadt.de, TU Darmstadt, Germany.

2573-0142/2021/6-ART212 $15.00
https://doi.org/10.1145/3461734

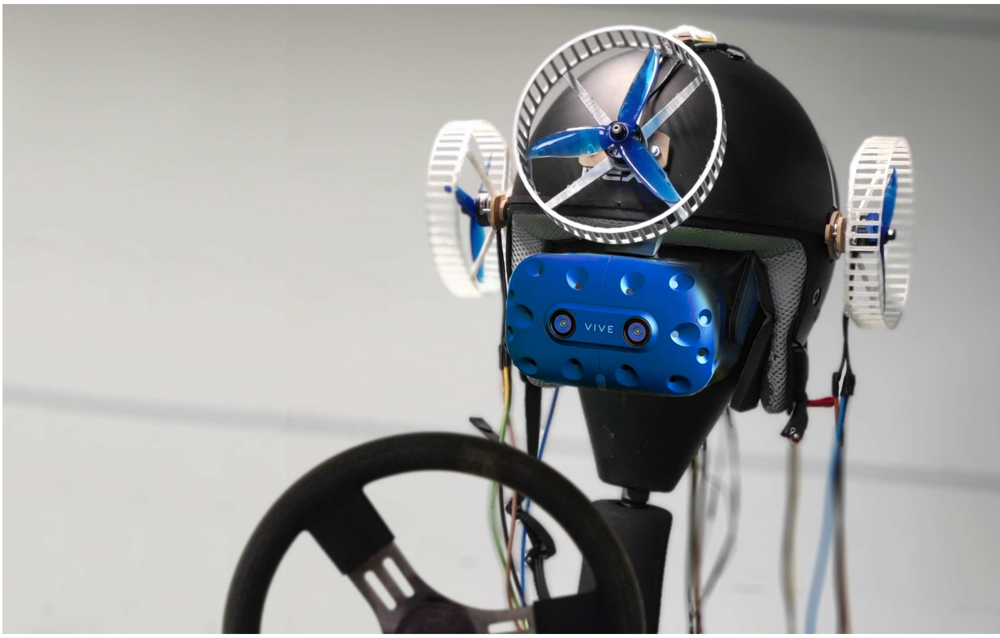


Fig. 1. We envision Odin's Helmet to enable the perception of g-forces in Virtual Reality. Our head-worn prototype has four propellers attached that actuate the direction of the user's head. Our vision is that the displacement, combined with the otolith organ and visual stimuli, simulate the perception of g-forces and self-motion in the virtual world.

muscle stimulation (EMS) to generate haptic feedback in VR while touching walls or interacting with more oversized objects, such as boxes [28] or the simulated impact of punches when the user is blocking their forearms. Already now, many handheld controllers offer tactile interaction, such as touching or grabbing objects [11, 44]. Hoppe et al. used drones as levitating tangibles to provide haptic feedback without any handheld devices [16, 18–20]. Whereas previous research was focusing on applying haptic feedback on various body parts, only few projects considered haptic feedback on the user's head. Takada et al. attached a drone to the user's head to help the user navigate while focusing on a smartphone by pulling the user into the needed direction[1]. Peiris et al. explored thermal feedback on head-mounted displays [32]. Odin's Helmet is inspired by two devices from previous work that we combined to build a head-worn device: Guggenheimer et al. presented GyroVR, a head-worn device that used spinning discs to slow down the user's head movement while turning, to simulate a hurt avatar [14]. Thor's Hammer placed an array of propellers in a hammer-shaped handheld device to generate haptic feedback and various levels of weights for handheld objects [15]. This paper presents Odin's Helmet, a conceptual reference implementation that combines the approach from Thor's Hammer to generate forces and GyroVR to manipulate head movements. Odin's Helmet uses one propeller at each side of a helmet to draw the user's head into one direction (see Figure 1). We show the efficiency of Odin's Helmet to exert forces on the user's head in a technical evaluation, showing that forces applied through propellers can be sufficient to convey a sense of balance. This would not only increase the level of immersion for

[1] Available in the Japanese language: www.iplab.cs.tsukuba.ac.jp/paper/domestic/takada_sigchi176.pdf

Fig. 2. Similarly to Odin replacing one eye and in exchange for knowledge, hence restricting his visual perception, the user trades the freedom of unconstrained head movement for the perception of simulated g-forces in VR. Odin's Helmet uses four propellers on each side of the device to simulate force as a modality for haptic feedback.

Virtual Reality systems, but also open up new design possibilities for building interactive systems that we present in the form of future use cases.

CONTRIBUTION STATEMENT

Our contribution is fourfold: (1) We explain how artificial head-worn forces manipulate the user's sense of balance in virtual environments. (2) We present a reference implementation of Odin's Helmet, a head-worn haptic feedback device that utilises four drone propellers to simulate g-forces in VR and actuate head motions (see Figure 1), hence improving the perception of applied forces in VR. (3) We describe the concept, implementation, and technical evaluation of Odin's Helmet. (4) Finally, we characterise use cases and applications that benefit from Odin's Helmet.

2 RELATED WORK

Previous researchers investigated various approaches to simulate forces in virtual reality. Here, several papers concentrated on how to provide haptic feedback using head-worn prototypes. Finally, we include past research related to human physiology and the vestibular system since the stimulation of the sense of balance is a central part of Odin's Helmet concept.

2.1 Force and Haptic Feedback

Handheld controllers are standard interaction devices for VR systems that are worn with the user's hands. Hence, a majority of research projects focused on handheld feedback devices. We

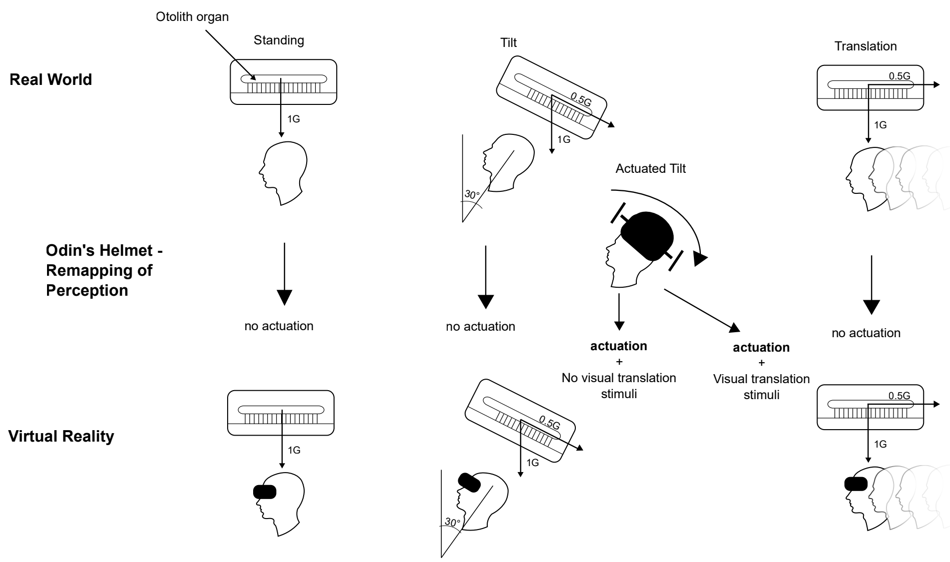


Fig. 3. The otolith organ is responsible for the sense of balance. The otolithic membrane is displaced by forces acting on the head, such as forces generated by translational movements or head tilts. Such forces result in similar displacements during head tilts as they would during absolute acceleration without head tilts [33]. This similarity combined with a visual stimulus, similar to the illusion of motion when watching a moving train while being stationary, serves as the base principle of Odin's Helmet. By combining the actuation of the user's head with a visual stimulus of movement, we envision a manipulation of the user's perception to feel translation while being stationary. The two variants of actuated tilt should therefore result in the perception of a force tilting the user's head, such as a simulation of acceleration in a car (i.e., actuation and no visual translation stimuli) and an illusion of self-motion (i.e., actuation and visual translation stimuli) [39].

investigated previous handheld feedback devices to adapt to a head-worn feedback system as a concept for Odin's Helmet. Ban et al. [5] explored directional force-feedback using motors to shift weights that created the sense of directional inertia of virtual objects. In contrast, Shifty [46] and Transcalibur [40] are handheld devices that use weight shifting elements to change the perception of different weights in virtual reality. Drag:On [48], a fan-like handheld device, develops this further by not only providing feedback via weight shifting but adds the feeling of resistance in VR by changing its shape and surface and thus its air resistance. New research trends focus on utilising drone propellers as haptic feedback devices. Thor's Hammer [15] used an array of propellers to provide 3-DoF feedback for use cases such as a feeling of dragging, tugging, and changing weight. Aero-plane [21], another project for changing weights in VR, used two small jet propellers to simulate shifting weights. Potential use cases include rapid weight shifting techniques in virtual reality, where interactive objects can weigh independently. LevioPole [37] provides mid-air haptic feedback by attaching two propellers units to a rod-like handheld device. Similar, Knierim et al. [22] and Hoppe et al. [18] used drones as levitating interfaces to provide hands-free tactile feedback. Here, we continue the increasing trend of utilising drone propellers to generate haptic feedback. A broad field of new actuation and feedback types opens up by adapting and applying previously investigated concepts to new areas.

2.2 Head-Worn Force and Haptic Feedback

Previous research has scarcely investigated head-worn prototypes that provide haptic feedback. In this context, Sand et al. [36] investigated the placement of a haptic feedback device that is mounted to the user's head. While they did not provide haptic feedback for the head itself, they used the head position to provide tactile feedback in mid-air. Face/On [45] combines heat pads and vibrotactile actuators to provide multi-sensory feedback of a burning torch on the user's face portion. Guggenheimer et al. presented GyroVR [14], a head-worn device that simulates weight by rendering inertia for head movements. The recently published project HeadBlaster explored an approach similar to Odin's Helmet by using a compressor and air jets to actuate the user's head [26], limiting the walkable space due to the need for a heavy air compressor.

2.3 Sense of Balance

Balance, acceleration, and vertigo are perceived through a combination of sensors all over the human body. The vestibular organ is a central contribution to those sensations. Spatial perception is a multi-sensory interplay within the human body, consisting of visual, proprioceptive, and vestibular input. The vestibular system, positioned in the inner ear, is the main contributor to the perception of rotation, acceleration, and balance [3] which is essential for spatial self-perception by being "*[. . .] a biological 6-DoF inertial measuring device*" as described by Mergner et al. [30]. The system detects motion even when moved passively without additional spatial cues from vision or acoustics.

The stimulation of the sense of balance is often neglected in current VR systems. Haptic Turk orchestrates multiple persons to simulate acceleration and movement for a VR hang gliding experience [9]. This approach created a human-actuated motion platform that followed the same principle as automated motion platforms such as CableRobot Simulator [31] or hexapods [38]. These platforms can simulate g-forces and acceleration for moving vehicles in VR. Due to these platforms' nature, they have high safety regulations and need a large area of operation. VRspinning is a 1-DoF Motion Platform that uses an actuated office chair to enable horizontal rotations [34]. Teng et al. enhanced this idea and added force output for rotation, tilt, and rolling to an office chair [42]. Von Willich et al. used the rotation and tilting properties of an office chair as an input modality for driving on a race track [43].

While the systems mentioned above rely on the physical manipulation of the sense of balance, other approaches artificially manipulation the sense. Galvanic Vestibular Manipulation (GVS) directly affects the sense of balance by directly stimulating vestibular reflexes through the application of electrodes, leading to head and body sways when a current is applied [12]. Byrne et al. explored the effects of vertigo in their game "Balance Ninja" causing the players to lose their balance through GVS. They also concluded that GVS is restrictive due to the direct attachment to the user's body and suggested the design of devices to be as little invasive as possible such as the use of headwear [7]. Further downsides are the extensive process of attaching the diodes directly to the body, being uncomfortable, and the need for an individualised calibration [7, 15]. These restrictions also may hinder greater immersion [2]. With Odin's Helmet, we present a novel concept to actuate the user's head to simulate VR forces.

3 ODIN'S HELMET

Potential VR experiences include recreation, gaming, online meetings, and training of complex or dangerous scenarios (i.e., driving a car [6, 10]). While the visual and auditory representations of such simulations are immersive, the representation of physical forces is still rudimentary. Feedback in virtual worlds makes the experience more immersive and enhances the user's judgment of their

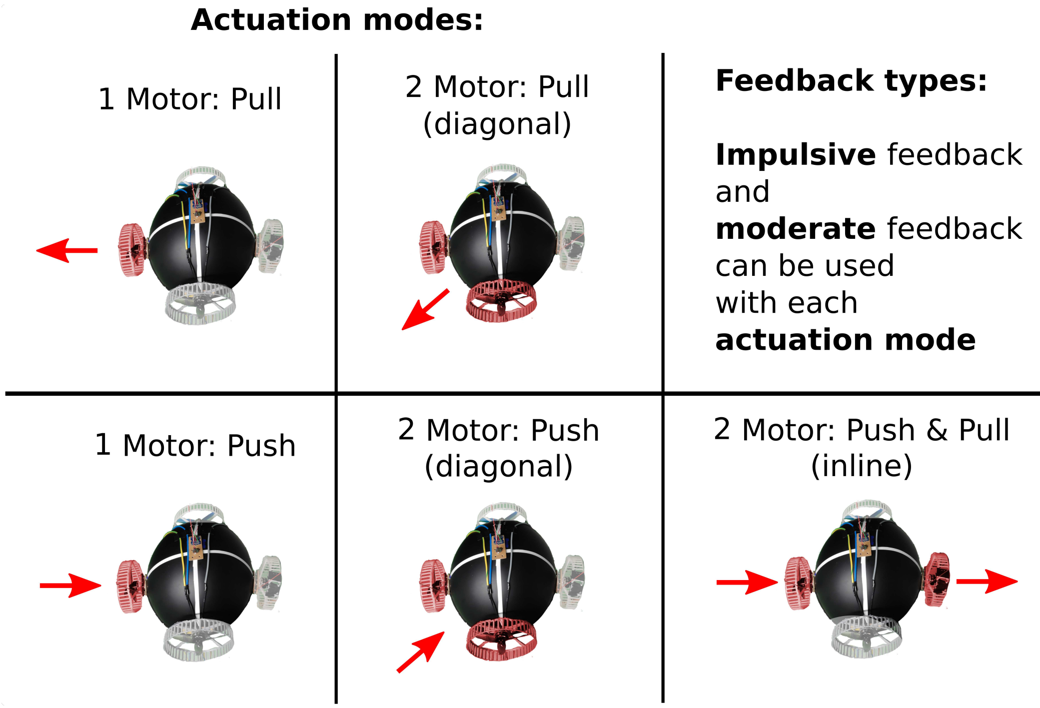


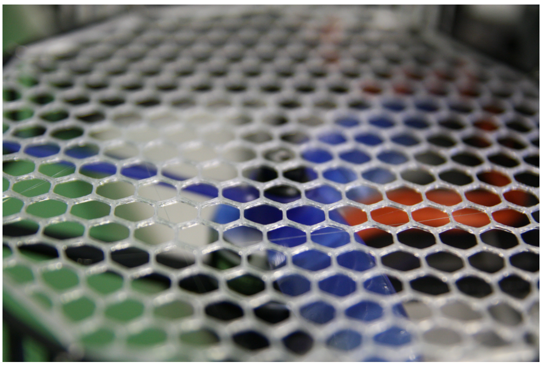
Fig. 4. Odin's Helmet offers two Feedback types: impulsive and moderate and 5 actuation types: *Push* forces the user's head to be pushed into a direction, while *Pull* redirects the user's head through pulling. *Push (diagonal)* and *Pull (diagonal)* use two adjacent propellers respectively. *Push & Pull (inline)* uses one propeller on each side.

own impact on the virtual world [17]. Odin's Helmet augments the user's head to perceive g-forces, hence adding a further dimension (see Figure 2). For example, forces that the avatar would perceive when driving into a curve on a race track are difficult to simulate by mere vibrotactile feedback. Odin's Helmet simulates the forces by actuating the user's head (see Figure 3). In the following, we present the concept of Odin's Helmet together with a reference implementation.

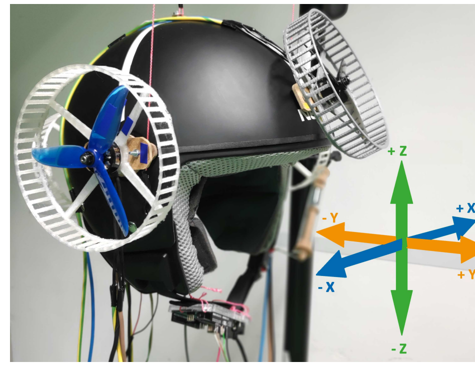
3.1 Actuation Concept

Odin's Helmet is inspired by Thor's Hammer [15] which utilises propellers to provide haptic feedback in the form of a handheld controller. Odin's Helmet transforms this concept into a head-worn device. The propellers enable pushing or pulling the user's head depending on the actuation mode (see Figure 4). The neck is the pivot point on which forces are applied. These forces manipulate the vestibular system located in the inner ear giving the user a feeling of g-forces being applied to their body.

The otolith organ, a part of the vestibular system, helps to detect movement of one's body (see Figure 3). When standing still, the otolith organ detects acceleration downwards with 1G. If there is a forward translation, the otolith organ detects a horizontal movement (e.g., 0.5 G) that leads to an orthogonal force downwards. By standing still and tilting the user's head backward, the same force of a "forward translation" (e.g., 0.5 G) can be detected while the downward force (1 G) is not orthogonal but at a smaller angle to the "forward" force. The angle of the downward force lets the user detect if an actual translation movement is taking place or if the head is tilted (see



(a)



(b)

Fig. 5. **(a):** A 3D-printed safety net is attached to the propeller case to ensure user safety. If desired, a tighter net can also serve as a mechanical barrier to limit the maximum generated force by restricting airflow. **(b):** Testbed for Odin's Helmet for early evaluation. The helmet is hung on the ceiling and spring feathers are used to measure force in Newton. An accelerator was attached at the top of the helmet to measure acceleration. Phonometers are placed inside the helmet and in one-meter distance to measure the produced sound levels.

Figure 3). However, we argue that due to the visual dominance the combination of the visual stimuli of movement and the actuated head tilting, the user cannot distinguish between a tilted head and actual forward movement as the forces result in a similar displacement of the otolithic membrane when comparing head tilts and certain acceleration [33]. This illusion of motion can also be witnessed when looking through a window at a moving train while sitting on a stationary train. Additionally, the proprioception of the tilted head matches the experience of the effect on the head when steering a car, where the head is also tilted. For the simulation of forces such as sudden acceleration or impact, such as hitting one's head, the actuated tilt can be applied without a visual stimulus of movement.

3.2 Conceptual Reference Implementation

We present a reference implementation of Odin's Helmet in the following. We designed Odin's Helmet to be rebuilt with low-budget off-the-shelf hardware and materials which are commonly used for FPV-drone racing. Odin's Helmet was equipped with four 5046c Triblade propellers combined with 2600Kv brushless DC electric motors that serve as actuators. The brushless electric motors were controlled through a 40 Ampere Electronic Speed Controller. All four motors were controlled using an Arduino board. The motors are mounted on the helmet and cushioned to reduce vibration and noise. One motor is placed on each side of Odin's Helmet (see Figure 5b). Two motors are mounted on the sides, one at the front (i.e., the upper center of the forehead) and one at the back of the head (i.e., close to the transition to the neck). The opposing motors are positioned in-line with the same motors to allow for an increase in actuation power and enable a faster stop by mutual cancellation. Here, Odin's Helmet supports the five actuation types pull, pull diagonal, push, push diagonal, and push & pull inline with the two feedback modes *moderate* increase (i.e., linearly accelerating) and *impulsive* increase (i.e., sudden increase in acceleration) of forces (see Figure 4). We have selected the five actuation types to investigate how the applied forces contribute to the overall manipulation of head movements. The two feedback types *moderate* and *impulsive* are envisioned to map the exertion of forces for different visual scenarios in virtual reality. For safety reasons, the propellers are embedded with 3D-printed cases and safety nets (see Figure 5a and Figure 5b). A tighter net can also be used to restrict the airflow and therefore serve as a mechanical barrier to limit the maximum generated forces. Odin's Helmet is powered using a 12V car battery. The car battery serves as a buffer for the electric motors that can be powered without interruption during moments of high current draw.

3.3 How Odin's Helmet Enhances the Perception of Virtual Environments

The concept of Odin's Helmet can be integrated into the design of future interactive systems. The system can actuate the user's head depending on changes in the world or user actions by mapping physical forces to events in virtual worlds. Odin's Helmet can use scripted events to trigger physical simulations through forces by the chosen engine. More detailed examples of potential use cases are found in Section 5.4.

3.3.1 States of Actuation. Odin's Helmet can achieve the following actuation states: a neutral position is achieved when the motors are turned off. Odin's Helmet remains in a neutral state. The motors are activated upon receiving an event. The motors start pinning and increase their speed to represent continuous and intensifying virtual forces (see Figure 4 for an explanation of the moderate feedback types). Alternatively, the motors start to spin fast upon a sudden and intense virtual event (see Figure 4 for an explanation of the impulsive feedback types). Depending on the desired feedback, the motors can prolong spinning to uphold the generated force, slowly decrease their speed, or instantly turn off. All changes (i.e., starting, ongoing, turning off) as well as the maximum speed of motors, and therefore maximum generated force, can be set depending on the desired strength of feedback and reactive behaviour.

3.3.2 Virtual Events. VR experiences are often created in game engines such as Unity3D. In these engines, game objects represent elements and objects of the virtual scene that can be placed in the scene, moved, and part of physics simulations. Such game objects can be a flower, a car, or something abstract like the user's head position. When an object is part of a physics simulation, it is possible to receive its current position, change in position, speed, and forces that affect the object. These forces and properties then can be mapped to the actuation capabilities of Odin's Helmet. For example, if a user is represented by a game object inside a car and a set threshold of force is exceeded, the motors of Odin's Helmet would be turned on and spin faster or slower, equal to the forces on the user game object.

This includes other events, such as collisions, which can be simulated. The game engine can detect the overlap of two game objects and then trigger a collision notification. This then can be mapped to the motors of Odin's Helmet. For example, the user's head gets hit in a virtual boxing match. Upon each hit, the detected collision will trigger a short and impulsive actuation to represent the received blow. By such events and mapping to Odin's Helmet actuation capabilities, the representation of physical forces is possible in a way that otherwise cannot be perceived in this form. All presented properties, threshold, and behaviours can be adjusted to align with the desired feedback design.

4 TECHNICAL EVALUATION

This section describes and presents a technical evaluation of a reference implementation of Odin's Helmet. The evaluation assesses the exerted volume and forces of the five actuation modes with the two feedback types *moderate* and *impulsive*. We describe the testbed in the following.

4.1 Testbed

The evaluation investigates the exerted forces in Newton (N) and the sound volume produced in decibel (dB). All five actuation modes (i.e., pull, pull diagonal, push, push diagonal, and push & pull inline) for each of the two feedback types *moderate* and *impulsive* (see Figure 4) were tested. We constructed a testbed to evaluate the forces that were simulated using our motor and propeller configuration on Odin's Helmet for each actuation mode and feedback type (see Figure 5b). Hence, we suspended Odin's Helmet on strings. Additionally, spring scales (i.e., a newton meter) measured the produced force in Newtons to a suspension bar and to the side of the helmet. We simulate two feedback types: a moderate acceleration in which the propellers subsequently start to spin until they reach their maximal spinning rate and an impulsive acceleration, in which the motors accelerate to their maximal spinning rate in the shortest possible time. Both feedback types were selected to simulate common situations typical in VR, such as accelerating a car (i.e., moderate) or perceiving a sudden impact (i.e., impulsive).

4.1.1 Moderate Feedback Type. The measurements for the moderate feedback type started with the motors spinning with 5% of their maximum speed, which was maintained for three seconds. Then, the motors accelerated to full speed in two seconds. This speed was maintained for one second. The motors decreased to zero rotations per minute in two seconds.

4.1.2 Impulsive Feedback Type. The motors spun with 5% of their maximum speed for four seconds in the impulsive acceleration scenario. The motors then increased the speed to 100% as fast as possible, which was held for one second. The motors were then immediately turned off.

4.1.3 Measurements. We used an accelerometer[2] to measure how the velocity of the helmet changes. The accelerometer was attached to the top of the helmet. The generated noise was measured with a phonometer that was placed inside and one outside of the helmet in the distance of one meter. All measurements were repeated 20 times. This procedure was repeated for each of the five previously mentioned actuation modes: *One Motor Push*, *One Motor Pull*, *Two Motors Push (diagonal)*, *Two Motors Pull (diagonal)* and *Two Motor Push & Pull (inline)*.

4.2 Results

Our testbed measured the forces and sound levels of each feedback type and actuation mode. A summary of the results can be seen in Table 1. We present and discuss our results in the following.

The impulsive feedback type showed the strongest force throughout all actuation modes. This behaviour was expected since impulsive feedback utilises the sudden use of available force of the motors. Impulsive pulling with one motor exerted more force than the other motor actuation modes. In contrast, two impulsive pushing motors resulted in more force than the other two motor actuation modes. Impulsive pulling and pushing with two motors inline results in the strongest force that could be measured with Odin's Helmet. Our design aimed at creating forces that do not exceed 10% of the maximal forces that are safe for this body part. In our case, this means limiting the forces to about 4N. In all but one case, we stayed in this range. For one case, the force measured was 5N (about 13% of the forces considered safe). This could be limited either in software or by adding a finer net over the propeller in a further iteration. Odin's Helmet will not damage the human neck since the cervical muscle strength among males withstands 72N and 41N for females on average [23] (i.e., assuming the users do not have previous neck injuries). The acceleration also generates in a safe range, as it does not exceed 0.3 G at any point during the experiment. However, sound levels that are above 85dB are considered critical. Hence, the use of hearing protection or

[2] www.analog.com/media/en/technical-documentation/data-sheets/ADXL335.pdf

Actuation Mode		**Feedback Type**	**Max. Force in N**	**Max. Sound in dB**	
				Inside	Outside
One Motor	Pull	Impulsive	**3.5**	107.2	95.3
		Moderate	2.0	104.2	90.0
	Push	Impulsive	3.0	107.7	**103.0**
		Moderate	2.0	**108.4**	98.5
Two Motors (Diagonal)	Pull	Impulsive	2.0	106.4	92.5
		Moderate	1.5	101.2	92.3
	Push	Impulsive	**3.0**	**108.7**	**104.1**
		Moderate	2.5	107.8	103.0
Two Motors (Inline)	Pull & Push	Impulsive	**5.0**	**106.9**	**98.8**
		Moderate	2.5	104.2	98.2

Table 1. Maximum measurement values of the five actuation modes for each feedback type. We utilised single motor as well as dual-motor settings to evaluate diagonal manipulations and two motors actuating in the same direction.

noise-canceling headphones will be necessary before users can experience Odin's Helmet. We are planning to use in-ear monitors used by professional on-stage musicians during high-volume live concerts. This offers a way of comfortable hearing protection that will still allow us to present the sounds of the VR scenes to the user.

5 DISCUSSION

We presented a reference implementation of Odin's Helmet, a head-worn device that uses propellers to simulate g-forces in VR. We conducted a technical evaluation of Odin's Helmet which investigates the exerted forces of different actuation modes and their accompanied sound levels. We discuss the implications of our results in the following.

5.1 Using the Right Actuation Mode for the Right Job

We measured the exerted forces and sound levels of impulsive and moderate feedback using different motor configurations. We find that different actuation modes combined with different feedback types allow the simulation of different situations in VR. On the one hand, our results show that combining two motors that pull and push the user's head in the same direction achieves the highest force when using impulsive feedback. Hence, two inline motors with impulsive feedback can be used in situations where sudden events happen (e.g., explosion next to the user in VR). Similar findings are present in the diagonal actuation using two motors and impulsive feedback. It is interesting to note that impulsive forces are lower when using one motor. This allows to regulate impulsive feedback types depending on the forces that should be applied to the user. On the other hand, we find that moderate feedback exerts lower forces when the propellers reach the maximum velocity. This is a scenario where g-forces are slowly applied to the user, such as in car driving scenarios. **User interface designer should use impulsive feedback if the mediation of sudden events in VR is of high priority.** Impulsive feedback can be delivered with different magnitudes to match the displayed VR experience depending on the number of motors in their respective pull and push configurations. **Moderate feedback is advised when feedback should be slowly added to the user's head to simulate the gradual application of forces.**

5.2 Sound Levels

Our results show that the sound levels are different per actuation mode and feedback type. Here, we find the lowest sound levels with one motor using a pull feedback type. Interestingly, one motor with an impulsive pull configuration provides the highest force with decent sound levels compared to the actuation modes and feedback types. **It is advisable to use one pulling motor if a force of 3.5 N is sufficient.** Designers should consider the other actuation modes if more forces are required. However, this represents a tradeoff as sound levels may increase with different actuation modes.

5.3 Limitations and Future Work

We acknowledge a number of limitations of our evaluation. We did not conduct a user's to investigate the overall forces that can be exerted using Odin's Helmet. With this, we prevent putting user's into danger before we understand the overall impact of the forces. However, our results show that the forces of our configuration are harmless [23]. We will conduct a user-centered evaluation of Odin's Helmet in the future. Furthermore, we did not investigate the correlation between different head shapes, propeller sizes, and noise levels. This includes changes in current draw which can influence the exerted forces on the user. These factors can influence the individual perception of the user. We will include these aspects as part of the future evaluation.

We acknowledge the potential presence of latencies between the controller that sends commands and the final force applied by the motors. Achieving the desired force levels can require several seconds. The latency between events in the virtual scene and the perceived actuation will be among the next relevant evaluation factors. While we will include this in the upcoming study, past research has shown that the motors' latency is negligible [41]. Odin's Helmet employs high sound levels. The use of hearing protection (e.g., noise-canceling headphones) or the suitable integration of the sound levels for the displayed VR scene is subject for future work.

5.4 Use Cases

We present use cases that benefit from the simulation of forces in VR in the following. We focus on the simulation of forces on the user's head and outline further applications besides the generation of haptic feedback alone. These examples show how Odin's Helmet can increase immersion and perceived presence. This can be achieved by mapping acceleration and deceleration – in different actuation modes – to events taking place in the virtual world. Events such as accelerating a car or bumping one's head will then trigger the actuation mode (impulsive/moderate) and actuated strength depending on the desired feedback design.

5.4.1 Training and Simulation. VR is a suitable technology to simulate scenarios that would either be too (a) complicated to be carried out or (b) too dangerous to be conducted in real environments [10]. VR training scenarios, such as professional driving on race tracks or flight simulations, are already in use to educate people [6]. These scenarios did not simulate forces that are present in the virtual environment, hence dismissing an important immersion factor. While hexapods are sometimes used for simulation of g-forces [1, 13], Odin's Helmet closes this gap by simulating these forces without the need for large equipment. The haptic feedback does not only help to increase the immersion and presence of the user but also helps to receive a better feeling of the virtual world. It helps user's to assess virtual situations better during training. For example, g-forces can be simulated when accelerating or decelerating in curves by tilting the user's head in the respective direction. Thus, forces can be applied relative to the forces in the simulation (i.e., a car is driving smoothly into a curve) or impulsively (i.e., the car crashes with another object). Ongoing accelerations become stronger by successively increasing the propellers' pull and push intensities, hence letting the user feel a continuous increase in speed.

5.4.2 Video Games. Odin's Helmet can augment virtual environments in video games by simulate forces that are commonly not represented with adequate haptic feedback. Previous approaches that mediated forces of the virtual world were accomplished via hand-held controllers [47], drones [18, 22], or electrical muscle stimulation [28, 29]. Odin's Helmet provides continuous haptic feedback, in contrast to previous approaches that provided feedback only for a short moment. Examples are acceleration scenarios in which the virtual avatar is subject to continuous or increasing feedback. Short, intensive feedback can be delivered during boxing scenarios in which the head is hit, close by explosions, the user bumping the avatar's head while taking cover, or being stopped from pushing the head through a virtual wall to see what is on the other side.

5.4.3 Redirected Walking and View.

"*Where the head goes, the body follows.*"- Ryan Holiday

A key principle in sports and martial arts is to move the head into the direction in which the body should move. If the head of a person is subtly moved by a mechanism, the body movement, and hence the walking direction of the user, can be manipulated. Odin's Helmet can make use of this by directing the user's head for redirected walking purposes. In contrast to previous approaches that utilised electrical muscle stimulation [4] to simulate infinite walking scenarios, Odin's Helmet eliminates the need for electrode attachments. Our system could gently navigate users through environments without on-skin stimulation. Further, Odin's Helmet could be used to direct the user's perception and focus on important elements of VR scenarios or 360-degree videos as a form of attention guidance.

5.4.4 Weather Simulations. Odin's Helmet allows variable propeller spinning directions and speeds. Environmental weather changes can be simulated by pulling and pushing walking users from the desired direction. The perception of wind can be simulated by using the airflow generated by the propellers as explored by previous prototypes [8, 24]. Forces simultaneously pull and push the user's head into the respective direction. Such illusions make scenarios in which the user feels breezes (e.g., during hiking scenarios when climbing a hill) more realistic. Adjusting the rotations per minute can increase or decrease the perceived level of wind, thus offering wind forces between soft breezes and storms.

6 CONCLUSION

We present Odin's Helmet, a conceptual head-worn system that uses propellers to actuate and direct the user's head with either impulsive or moderate feedback. We envision Odin's Helmet actuate the user's head, hence stimulating the otolith organ, which is responsible for the sense of balance. Odin's Helmet utilises four propellers that are mounted on the sides, front, and back of the helmet as actuators using five actuation modes and two feedback types. Finally, we present several use cases that benefit from the simulation of g-forces using Odin's Helmet.

A technical evaluation shows that the system does not exert excessive force on the user's head and does not exceed the physical limitation of the human neck, hence not impacting the user's health. However, precautions should be made regarding produced sound by using adequate hearing protection. Finally, Odin's Helmet uses affordable off-the-shelf hardware and actively encourages to recreate of the prototype with different settings. We are confident that haptic feedback and the simulation of forces are going to be important variables for immersive Virtual Reality (VR) experiences. Every sense that is involved in the experience adds to the immersion and therefore increases the perceived presence. The simulation of g-forces and stimulation of the sense of balance is often neglected, especially in commercially available VR systems. The concept of Odin's Helmet shows how g-forces serve as a new type of feedback that paves the way for future interfaces and use cases that augment the user's sense of balance and self-motion in virtual environments.

ACKNOWLEDGEMENTS

This work was supported by the European Union's Horizon 2020 Programme under ERCEA grant no. 683008 AMPLIFY.

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Received February 2021; accepted April 2021